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FINAL TECHNICAL REPORT

ONR GRANT # N00014-87-K-0009

Douglas R. Caldwell
OSU Omnibus

PRIMARY SCIENTIFIC RESULTS

ABBOTT We successfully deployed and recovered a Lagrangian drifter equipped with a suite of bio-optical sensors in 1987 and 1988. These sensors, coupled with nutrient and phytoplankton samples collected by Codispoti and Blasco using an automated system on the same drifter, showed that there were considerable changes in the bio-optical properties of the filament as it moved offshore. In particular, the fluorescence response (both solar and sun-stimulated fluorescence) varied considerably between nearshore and offshore. Evidence of phytoplankton growth during the day and subsequent zooplankton grazing at night was also obtained from the beam transmissometer.

CZCS imagery showed that the appearance of filaments varied seasonally north of Point Conception, being most pronounced during the upwelling season. They appear earlier (May-July) off the California coast than off Oregon/Washington/British Columbia (August-September). Distinct filaments appear off the Baja California peninsula during fall and winter. Decorrelation analysis indicates that SST pigment are strongly affected by physical processes and that the decorrelation scales vary considerably depending on location within the filament structure.

Analysis of the size structure of the phytoplankton community indicates that there may be mixing between nearshore phytoplankton communities (typically dominated by large forms) and offshore communities (typically dominated by small forms) as the filament meanders south from Cape Mendocino to Point Arena.

ALLEN/WALSTAD Assimilation modeling of the CTZ dynamic height data has shown that for the 1987 pilot experiment the vorticity dynamics is dominated by a conversion of thermal to relative vorticity as the offshore jet enters an anti-cyclonic meander. Associated with this conversion is an upward vertical velocity of 15 m/day at 100 m depth. These processes are consistent with baroclinic instability. A method for the consistent assimilation of shipboard acoustic Doppler current profiler (ADCP) measurements has been developed and is being evaluated. An assessment of the ability of intermediate models, as applied to the shallow-water equations, to represent flow over O(1) topographic variations typical of the continental slope have shown that intermediate models can produce substantially more accurate solutions than the quasigeostrophic approximation and that they can be solved more efficiently than the primitive equations.

CALDWELL/MOUM/PAULSON During the first (1987) field experiment we obtained several hundreds of kilometers of thermistor chain tows, more than 900 underway RSVP microstructure profiles, and continuous ADCP profiles and surface meteorology. An intense recirculating feature off Pt. Arena was examined in detail. Three transects of the feature were executed on 3 consecutive days.

In 1988 we monitored the filament structure along the D-line of the CTZ grid. We obtained more than 2000 RSVP profiles and more than 1000 km of thermistor chain tows on thirteen transects. Also 2 sets of RSVP profiles (total 100) were made with an attached laser/fiber optic, high-resolution fluorometer (Cowles/Moum).

Data reports are available describing RSVP observations from each of the experiments. Data reports describing towed chain data and surface meteorology are in preparation. A manuscript which deals with the correlation between sea surface slicks and surface convergences observed during the 1987 experiment has been submitted for publication. (Moum and Carlson, "Sea slicks and surface convergences"). A second manuscript which describes the detailed structure of the filament observed in 1987 is now in manuscript form (Dewey, Moum, Paulson, Caldwell and Strub, "Momentum balances and transport estimates from meridional transects across a current meander during CTZ 87").

CARLSON We have expanded the size and capabilities of our real-time surface microlayer sampling capability (SCUMS). The larger sampler works in a wider range of wave conditions, self-steers, and measures surface properties with better resolution and precision because the detectors are immediately next to the sampler. We have added measurements of near-surface temperature and conductivity, and wind speed on the sampler. We have extensive SCUMS data sets from Maine, the North Pacific (CTZ 1987 and 1988), Bermuda, and San Diego with information microlayer properties and exchange processes. The sampler has become attractive as a platform and a data source for other measurements, e.g. of surface wave slopes by E. Bock, of radar backscatter by D. Trizna, and of surface acoustic properties by J. Vesecky et al.

During CTZ 1988 we tested a fin mounted outboard to the SCUMS which carried temperature and turbulence sensors. We demonstrated the feasibility of an outboard thermistor array and of measuring near-surface turbulence.

We developed chemical techniques to measure molecular-scale viscosity, seawater protein, and seawater phenols. We demonstrated that slicks are always more viscous than underlying water or adjacent unslicked surface water. We also found that microlayer viscosity was correlated with microlayer UV absorbance, suggesting a predictive relationship. We extended the fluorescence depolarization technique to measure viscosity on several molecular scales. We also measured seawater protein by our modification of the BCA (bicinchoninic acid) assay and found a correlation between microlayer protein enrichment and microlayer UV absorbance enrichment. We developed an aqueous derivitization technique for seawater phenols, and showed that tracer and natural phenol photodegradation is greatly enhanced in slicks, in a manner related to the UV absorbance enrichment of the slicks.

COLLIER Analytical methods have been developed to study the oxidation state of Fe <u>in situ</u>. Initial application of these methods suggest the presence of Fe(II) within the plume near a hydrothermal vent. The distribution of Mn has been shown to be consistent with a slow oxidation and scavenging rate relative to its decrease in concentration due to dilution. A near-field particulate manganese anomaly may be removed locally by intense scavenging and deposition.

COWLES/SMALL We recorded underway plant pigment fluorescence during all seven CTZ cruises of the R/V WECOMA during 1987 and 1988 using flow-through Turner Designs fluorometers, measuring both chlorophyll and phycoerythrin pigment concentrations. We obtained approximately 1900 hrs of continuous, underway data for phytoplankton pigment concentration, to be combined with temperature, salinity and nutrient data from other investigators. In addition, we obtained fluorescence profiles along with each CTD

cast on all cruises, for a total of over 400 profiles. We are currently merging the underway plant pigment data with all the other underway data, synchronizing all measurements to a common time base, and corrected position data. We will then be able to provide high resolution surface maps of all properties measured during 1987 and 1988. We conducted over 30 grazing studies during a 29 day period aboard the R/V WASHINGTON in June and July, 1988. The quantity of plant pigment in zooplankton guts was determined in and around the cold filament, both day and night. In addition, the rate of gut evacuation was determined for several species of zooplankton.

DE SZOEKE The balances of heat and momentum in the upper ocean during MILDEX (the Mixed Layer Dynamics Experiment), 650 km off central California, were examined using observations of currents, temperature, winds, and heating. Near-surface currents were partially wind-driven, and partially associated with deeper low-frequency currents, not coherent with the wind. The latter were sheared, turned significantly with depth, and were nearly geostrophically balanced. Advection by these currents was significant in the long-term (20 days) heat budget of the surface layers. Surface currents in the near-inertial frequency band, measured during this experiment below two platforms separated by 55 km, differed in their inertial response to a frontal passage on 1 November by 10 cm sec^{-1}. Model currents computed from wind records from the two platforms reproduced most of the features of the observed inertial currents, and explained the disparity in currents between the two locations. This was due to differences in the weak winds preceding the front, which drove inertial currents of approximately 5 cm sec^{-1} in opposing directions at the two sites.

The moored current meters from OCEAN STORMS, recovered in July 1988, show remarkable vertical propagation of energetic packets of near-inertial currents from the surface to more than 200 m depth during 10-15 days after frontal passages at the surface. A quantitative model using ray-tracing theory has been prepared to study these observations and relate the vertical propagation of the group to the characteristic properties of the surface forcing.

A model of steady wind- and buoyancy-driven ocean circulation has been developed with a number of new features, including longshore wind, and upwelling at the eastern boundary, that can modify the flow near the boundary substantially. The model can be applied to study the flow in the eastern North Atlantic near the site of the proposed Oceanic Convection and Subduction Experiment.

A model of time-dependent wind-driven upwelling at a coastal boundary has been developed. The model shows the rapid development of density fronts at the coast following upon suitable wind forcing and their subsequent advection offshore. The fronts are formed essentially by the rapid eruption at the surface of the submerged thermocline.

DILLON/PADMAN We established that the double-diffusive heat flux in the Beaufort Sea is too small to account for the observed basin-wide, long time scale heat transport; other processes, such as intermittent turbulent mixing events, or near-shore processes, must be invoked to explain large-scale observations. We also found that often-used techniques for estimating the momentum transport from turbulence measurements in the Equatorial Pacific may be faulty; internal waves may be more important for

momentum transport in the Equatorial Pacific than is turbulence driven by the large-scale mean shear.

DUNCAN

Current Status - All samples have now been collected from the aseismic ridges of interest: the Walvis Ridge, the Rio Grande Rise, the Cameroon Line, and The Bahia Pernambuco Seamounts. These were recovered by dredging during four cruises within the period of research support, through the cooperation of other research groups. A large sample collection existed from previous cruises and deep-sea drilling. After careful selection all suitable volcanic material has been dated using the $^{40}Ar/^{39}Ar$ technique. These ages are reproducible and demonstrate that these linear chains of volcanoes and ridges were formed over stationary hotspots.

We are also completing geochemical analyses for the entire sample set, including major and trace elements for newly collected samples by X-ray fluorescence methods and isotopic compositions by mass spectrometry, to trace the contribution of melts from hotspot spreading ridge and sub-continental mantle material to the construction of volcanic features in this region. We are currently preparing publication of these results in a series of papers on the dating, plate modeling, and geochemical compositions.

Significant Process (1) We have shown that the Walvis Ridge, the Rio Grande Rise, the Cameroon Seamounts, and probably the Pernambuco and Bahia Seamounts are hotspot lineaments, showing age-progressive volcanism (O'Connor and Duncan, 1984 and submitted). (2) We have identified the time at which the Mid-Atlantic Ridge migrated westward away from south Atlantic hotspots to be 60 or 70 Ma. This corresponds to changes in the composition and state of compensation of the volcanoes formed before and after this time (O'Connor and Duncan, submitted). (3) We predict that basalt compositions change from spreading-ridge dominated (MORB) to hotspot-dominated at about 60 Ma. (4) The Tristan hotspot began at 125 Ma with rapid eruption of the Parana and Etendeka flood basalts as rifting began in the South Atlantic. This supports correlations elsewhere between hotspots and flood basalts (e.g. Deccan Traps-Reunion hotspot). (5) Through computer plate modeling we have linked hotspot tracks in the South Atlantic to those in the North Atlantic and Indian Oceans to determine that hotspots are fixed with respect to one another on a global distribution and hence constitute a valuable reference frame for plate motion and reconstruction studies (McDougall and Duncan, 1988). (6) We have further demonstrated the applicability of the $^{40}Ar/^{39}Ar$ radiometric technique in determining reliable crystallization ages for altered volcanic rocks from the ocean basins.

OLTMAN-SHAY

In the past biennium, we published several results from the SUPERDUCK data set. Two of the most recently submitted papers describe both the kinematics of shear waves observed in the nearshore during SUPERDUCK (Oltman-Shay, Howd and Birkemeir, submitted) and a theoretical model of their dynamics (Bowen and Holman, submitted). These waves had been previously unknown to the nearshore, yet appear to be a fairly ubiquitous process at the SUPERDUCK field sites. Thus far we have found that: (1) Energetic shear waves have typical longshore wavelengths of a few hundred meters; an order of magnitude smaller than the shortest surface gravity waves (mode 0 edge waves) at the same frequency. (2) Shear waves typically dominate other processes in the FIG frequency band, occasionally

intruding into higher frequencies. (3) Shear waves have their energy concentrated along an approximately linear dispersion line in wavenumber-frequency space, distinct from surface gravity wave dispersion lines. (4) Their celerity is approximately 1/2 to 1 times the measured mean longshore current magnitude and is occasionally dispersive with long wavelengths traveling slower. (5) Shear waves propagate in the direction of the mean longshore current with celerities and velocity amplitudes that increase with increased mean longshore current magnitudes. (6) Shear wave kinematics are successfully explained in terms of shear instability of the mean longshore current with conservation of potential vorticity the restoring mechanism.

Our application of real time image processing of video data has provided, for the first time to nearshore studies, a long term quantitative data set of sand bar morphology. This technology was developed in our lab under ONR funding. The utilization of intensity patterns of waves breaking over the sand bar to map bar location was theoretically modeled in terms of wave dissipation and verified with ground truth survey data (Lippmann and Holman, 1988). The power of this technique resides in its simple acquisition and quantitative nature. Two years of daily video data (beginning during SUPERDUCK) was acquired, resulting in a paper that statistically describes the spatial variability and temporal stability (O(days)) of sand bar morphology (Lippmann and Holman, submitted). Significant results are: (1) A bar morphology classification scheme was developed that uniquely defines eight bar types based on four objective, processes-oriented criteria. (2) Shore-attached crescentic bars are the most stable and generally form 5-16 days following peak wave events. (3) Linear bars are very unstable and predominate during storms. (4) On-offshore bar movement is positively correlated with wave height with large positive changes in wave height preceding offshore bar migration on the order of less than one day. (5) Large scale (O(100 meters)) three-dimensional morphology statistically lags storm events by 5 to 7 days.

HUYER CTD/ADCP surveys have shown that there are onshore-directed as well as offshore-directed jet-like currents in the coastal transition zone off northern California. Both the onshore and offshore jets are narrow, both have transports exceeding 1 Sv, and both exhibit strong vertical shear. Both the onshore and offshore jets seem to be segments of a meandering current that flows generally equatorward along the coast. The meanders seem to evolve over time-scales of a few weeks. Advection by the equatorward surface current and the poleward California Undercurrent results in significant inhomogeneities of the water properties off northern California.

KADKO It has been demonstrated that the use of radiotracers, specifically radon-22 in the Coastal Transition Zone program, are useful in unraveling mixing processes in the upper ocean. The radon results show very clearly that subduction is occurring within the coastal filaments, and that corresponding deep maxima of chlorophyll are surface derived, and not in-situ developed or a result of particle sinking. The time scale of radon constrains the age of these layers since atmospheric contact, to be less than about one week.

KOSRO CTD/ADCP surveys have shown that there are onshore-directed as well as offshore-directed jet-like currents in the coastal transition zone (CTZ) off northern California. Both the onshore and

offshore jets are narrow, both have transports exceeding 1 Sv, and both exhibit strong vertical shear. Both the onshore and offshore jets seem to be segments of a meandering current that flows generally equatorward along the coast. The meanders seem to evolve over time-scales of a few weeks. Advection by the equatorward surface current and the poleward California Undercurrent results in significant inhomogeneities of the water properties off northern California. Time series of upper ocean current profiles were also successfully collected from ADCPs moored across two current jets, one in CTZ, the other in the Gulf of Tehuantepec off southern Mexico.

LEVINE Over the past two years a 10-month time series of temperature, conductivity and velocity was obtained from a subsurface mooring as part of the Ocean Storms experiment. Preliminary results indicate that significant mixing occurs throughout the pycnocline and does not just take place at the base of the mixed layer; internal waves undoubtedly play an important role in this process. An analytical solution of the generation of internal waves by moving ice keels was developed to aid in analyzing data from AIWEX. A new technique of "elliptical decomposition" was developed to extract the internal tidal signal from data; the method was applied to observations from MILDEX.

LEVINE/PAULSON The past two years were filled with planning and preparation for the deployment of temperature, conductivity and velocity sensors below the Arctic pack ice, as part of CEAREX. The field program is just beginning as we write; scientific results will follow.

MATE The most recent application of Argos technology by OSU demonstrates its potential. A pilot whale, Globicephala melaena, fitted with an Argos (satellite-monitored) transmitter was released off Cape Cod in the vicinity of other pilot whales in June 1987 and tracked for 95 days (the full life of the transmitter). The whale's location was determined 479 times as it moved at least 7,600 km (x = 80 km/day). The maximum daily distance traveled was 234 km (x = 9.7 km/hr). Average speeds of 16 km/hr were sustained for periods > 3 hrs, while the 95 day average was 3.3 km/hr. The study provided quantitative data on all 187,866 dives > 6 s for 93 days. The number of dives in a 12 hr period varied from 636 to 1625 (x = 2,020 dives/day). The average dive duration during 12 hr periods varied from 24 s to 62 s (x = 40 s). The maximum dive duration was 548 s (9.1 min.). Eighty percent of all dives were less than 2 min. in duration. Most deep dives were at night and probably represent foraging activity as they coincided with upward migration of the deep scattering layer and the pilot whale's primary food, the short-finned squid (Illex illecebrosus). Resting at the surface for up to several hours occurred every four to seven days and was most common immediately after sunrise. The tagged whale remained vigorous (healthy) throughout the experiment. This is the longest duration experiment for remotely monitoring a free-ranging whale's movements and dive patterns. It is the first detailed account of a rehabilitated whale's successful reintroduction into the wild.

MILLER Optimal interpolation has been implemented with the Harvard Open Ocean Model and used to analyze the OPTOMA11 data set. A new technique has been developed for assimilating satellite altimetric data which does not depend on knowledge of the geoid or upon any reference state. The question of observability, i.e., whether or not a model in conjunction

with a given set of data completely determines the state of the system under study has been investigated using techniques adapted from the applied mathematics literature. The practical effect of the ill-posedness of the open ocean boundary problem for the quasigeostrophic model has been determined by analytical and computational examples. The results of this study were published in Tellus in 1988.

MOUM

During the past two years, progress has been made in the following areas: (1) From our equatorial measurements, we have detailed the evolution of the diurnal surface layer and suggested that high-wavenumber internal gravity waves are critical in determining vertical transports due to turbulence. We are focussing more closely on this aspect with several specific examples. (2) Two successful seagoing experiments have been completed as part of the Coastal Transition Zone experiment. With the data now in good shape, we are beginning to look at the finely-detailed structure of the cool filaments of the CTZ. In collaboration with D. Carlson, we have merged sea surface chemistry data and physical oceanography data acquired during the CTZ87 experiment to try to understand the mechanisms responsible for sea slick formation. In collaboration with T. Cowles, a series of successful experiments to measure the microstructure of chlorophyll were performed during CTZ88. We are exploring the correlation of this parameter with simultaneously-measured physical microstructure. (3) A new measurement of microstructure vertical velocity has been demonstrated and has been applied to the calculation of turbulent heat transport using the eddy correlation technique.

PAULSON

During the past two years we have: 1) published a paper showing that the spectrum of towed thermistor chain observations in the North Pacific subtropical frontal zone is consistent with Charney's theory of geostrophic turbulence, 2) published a paper showing that the internal wave field under the pack ice in the Beaufort Sea has a different spectral shape and is more than an order of magnitude less energetic than in the low-latitude ocean, 3) as part of the Ocean Storms experiment, measured energetic inertial currents generated by the passage of storms over the Northeast Pacific, and 4) as part of the Coastal Transition Zone experiment, made towed thermistor chain observations off Northern California of the fast-flowing cold filaments which extend from the coastal upwelling zone offshore for several hundred kilometers.

SMITH

We have utilized moored Acoustic Doppler Current Profilers to investigate the near surface (20m-100m) velocity fields during two studies of high velocity "jets": The California cool "squirts" in the Coastal Transition Zone and the wind-forced "jet" in the Gulf of Tehuantepec. Both field experiments occurred within the past ten months and each utilized three moored ADCPs, which provided complete data sets. In both experiments velocity data was obtained near the core of the jet [O(1 m/s) at 25 m] and outside the jet. Although the forcing mechanisms and the horizontal scales (CTZ: 40 km; Tehuantepec: 100 km) were different, the vertical shear in the upper 100 m was similar [O(0.005 m/s/m)] under the core of the jets. The CTZ jet meanders sinuously in space and time; the Tehuantepec jet appears to form a clockwise rotating eddy. Our nearly perfect success with the ADCPs is the result of the careful (and painstaking) familiarization and testing of the new (to us) instrumentation done during the previous year.

STRUB/THOMAS Estimates of surface velocity fields from sequences of AVHRR images are often in qualitative agreement with field measurements, although they may underestimate the velocity magnitudes by a factor of 2 in narrow jets and regions of disagreement do occur. These images suggest that the seasonal evolution of the large-scale (33°N-48°N) flow field followed similar patterns in May-July in 1987 and 1988. Features associated with meanders in the southward flow appear in May at the major capes along the coast. By mid-July these features evolve into long filaments extending 300-500 km westward to southwestward. The filament studied in 1988 was a strong offshore jet which terminated in an offshore cyclonic eddy with onshore flow to the south of the filament. Similar filaments continue to be seen in the imagery until at least the end of September.